A Heuristic Solution Based on Clarke & Wright's Savings Algorithm for the Optimization of Sludge Hauling: the case of a Portuguese company

Jeysa Passos
VALORIZA - Research Center for Endogenous Resource Valorisation,
Polytechnic Institute of Portalegre
Portalegre, Portugal
jpassos@ipportalegre.pt

Gonçalo Lourinho
VALORIZA - Research Center for Endogenous Resource Valorisation,
Polytechnic Institute of Portalegre
Portalegre, Portugal
glourinho@gmail.com

Octávio Alves
VALORIZA - Research Center for Endogenous Resource Valorisation,
Polytechnic Institute of Portalegre
Portalegre, Portugal
octavio.alves@ipportalegre.pt

Paulo Brito
VALORIZA - Research Center for Endogenous Resource Valorisation,
Polytechnic Institute of Portalegre
Portalegre, Portugal
pbrito@ipportalegre.pt

Abstract— **Sewage sludge originating from wastewater treatment plants (WWTPs) can be a major cause of environmental pollution and their appropriate management should be viewed as a priority. A critical aspect in sludge management practices is route optimization since significant costs are associated with the transportation of waste. In this work, we propose a heuristic solution based on Clarke-Wright savings method for the sludge collection problem of a Portuguese company within a perspective of reducing collection costs (transportation) and negative impacts on the environment. Two case studies were considered in the methodology: the first one focused on the comparison between the general weekly collection plan presently used by the company and the solution generated by CW algorithm (Case Study A); the second one explored a new hypothetical scenario centered on the expansion of the company's activities (Case Study B). In general, the application of CW method led to a decrease in traveled distances and transportation costs, as well as carbon dioxide emissions. Specifically, with the adoption of the optimized plan in Case Study A we found that a single vehicle (instead of three) would be capable of performing sludge hauling operations in a given week leading to total weekly savings of 346 km, representing a decrease of almost 40% for both cost and pollutant emissions. Regarding Case Study B, the model suggests that for about 76% of the initial cost, the company would be capable of attending twice the number of customers, i.e., via route optimization, it is possible to expand their client portfolio while still creating savings. Moreover, a sensitivity analysis (SA) was carried out in order to check the robustness of results when undergoing changes in the input parameters. We found that vehicle capacity and fuel price are two important factors in route optimization with model results greatly influenced by changes in both parameters.**

Keywords— Clarke and Wright, Vehicle Routing Problem, Sludge, GHG emissions

I. INTRODUCTION

The rapid rise in population along with increasing industrialization in recent years have enhanced the production of sewage sludge in wastewater treatment plants (WWTPs) [1], increasing the need of their appropriate management in order to avoid several environmental impacts. In fact, proper treatment and disposal of sewage sludge is a critical element in environmental planning since improper disposal or inadequate treatment may result in the contamination of groundwater and drinking-water supplies, as well as public health problems. Biological WWTPs have been employed throughout the world to treat municipal wastewater and sludge effluent streams are an inevitable by-product. Although the process is efficient in removing organic matter, large amounts of sludge are generated and thus its management is becoming an issue of growing importance [2], [3]. The average annual production of excess sludge, for example, climbed to 240 million wet tons in Europe, USA and China combined [4]. The main methods for sludge disposal have been landfill deposition, agricultural use, and incineration, all incurring very large costs (e.g. 30–100 € per wet ton in Europe) [4]. Therefore, developing strategies for reducing costs in sludge management is of paramount importance.

Recently, European policy makers have been introducing many programs, developmental strategies, and legislation focused on methods leading to waste stabilization and safe recycling. These methods aim to recover valuable raw materials from potentially dangerous effluent streams and processing them in order to enable their use in agriculture, and industry for energy recovery. In this way, pro-ecological management of sewage sludge should be viewed as a priority [3]. In fact, its importance as a valuable source of matter and energy has been appreciated [5] since it can be considered an available resource for renewable energy. Some technologies applied to recycle and recover energy from sewage sludge are: incineration (in plants designed only for thermal treatment of sludge as the main feedstock); co-incineration (in concrete plants, in the energy sector, and in waste incineration plants); and alternate thermal methods (for solid fuel production processes) [3], [5]. Sludge management practices have also received careful consideration in the European Union (EU), especially the operation of the collection system. One of the factors that have been covered given its contribution to increasing pollution and environmental impacts is the

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©2018 IEEE

generation of greenhouse gases (GHG) through transportation. Nevertheless, the environmental impact of air emissions produced by refuse vehicles is a fairly recent concern due to the increase in environmental standards [6]. Emissions from trucks and buses increased by 36% between 1990 and 2010 and continue to grow. Recently, these emissions represent around 30% of all road transport emissions and 5% of all EU in terms of CO2 [7]. Based on this, emission factors have been introduced in order to estimate the amount of GHGs released per unit of energy, mass, or volume. They are used with increased frequency for the accounting and reporting of GHG from waste management [8], with the GHG emissions resulting from diesel ranging from 0.4 - 0.5 Kg $CO_{2\text{-eq}}$. L^{-1} [9]. In order to reduce the environmental impact caused by transportation, many strategies have been explored recently, including the improvement of management systems by the optimization of waste collection.

It is known that the collection of the waste represents the major part of total expenditure in solid waste management. Thus, route optimization might be considered one essential approach for cost reduction within the industry [10]. In the area of combinatorial optimization, the Vehicle Routing Problem (VRP) is one of the most studied problems. VRP is a generic name given to a whole class of problems in which a set of routes for a fleet of vehicles must be determined for a number of geographically dispersed customers [11]. It is generally considered a complex problem but it is commonly used to define optimal routes for the vehicles that collect waste [12]. Specifically, the concept consists of obtaining routes that minimize the costs of distributing a fleet of vehicles operating from one or more central depots, subject to the restrictions relevant to the specific delivery or collection operation. A VRP is therefore defined by three fundamental factors: decision, goals, and restrictions [13]. Generally, it is easy to solve the basic routing problem: either a set of nodes and/or arcs to be serviced by a given fleet of vehicles (with no restrictions on the periods) or the order of visiting points is considered to define the problem and achieve a solution, i.e., to build a low-cost and feasible route for each vehicle [14]. In logistics management, the VRP plays a central role in the efficiency of the operational planning level of distribution and/or collection management, producing economical routes that contribute to the reduction of costs, while simultaneously offering significant savings in all related expenses (fuel costs, driver salaries, etc.) [15]. VRP has been extensively studied in the literature and applied to many real situations, for example, to optimize the distribution of fresh milk [16], and to service large-scale emergencies like natural disasters and terrorist attacks [17]. In this context, the development of models for solving specific problems plays an important role in optimizing situations that are part of our daily life. One of the most widely used methods for solving VRP problems is heuristics. Heuristic methods are practical strategies that generate approximate or sub-optimal solutions, allowing to find good solutions in a shorter time and requiring less computational effort. Heuristics usually adopt empirical grouping rules or techniques that are based on economies and can add or exclude nodes. The present work makes use of these heuristic approaches and is aimed to develop and implement a logistic optimization method for the sludge collection system used by a Portuguese company. Specifically, in this study, we propose a methodology based on the Clarke-Wright algorithm (CW) to solve the sludge collection problem of the referred company within a perspective of reducing transportation costs and negative impacts on the environment.

II. Literature Review

VRPs intend to find a given set of routes that simultaneously minimize both the total cost of the service and the total distance that needs to be satisfied by a fleet of vehicles with determined capacity. In practice, routes are planned by taking into account some constraints such as the fact that each customer can only be visited once and by a single vehicle, and all vehicles start and finish from a common distribution center known as depot. Within this basis, finding a solution to the problem allows the minimization of operating costs, usually by decreasing the number of vehicles needed and the total distance or traveling time [18].

VRPs can be considered as the junction of two other well-known problems, namely the Traveling Salesman Problem (TSP) and the Bin Packing Problem (BPP) [19]. In the work developed by [20], for example, an optimal waste collection and transportation scheme was proposed to Kolkata city, India, based on the TSP. The integrated waste management system was divided into four parts and for each part of the system a route optimization to decrease transportation cost was proposed. More than 30% of the total waste collection path length was reduced with this method representing significant monetary savings in the waste management operations. Despite providing optimal solutions, these approaches do not consider the specific amounts of waste (demand) that have to be collected on the same route. To deal with this issue, the problem can be modeled as the Capacitated Vehicle Routing Problem (CVRP) in waste collection systems [21]. CVRP is a problem which considers an additional constraint related with the capacity of the vehicle, i.e., a fixed fleet of vehicles of uniform capacity must service known customer demands for a single commodity, starting from a common depot at minimum transit cost [15], [22]. The objective of CVRP is thus to build a feasible set of vehicle routes that minimize the total traveling distance and/or the total number of vehicles used [19]. These have been receiving increased attention from researchers in recent years and have been widely studied in the area of combinatorial optimization. In the work developed by [12], for instance, a combinatorial optimization problem (CARP) was solved in order to obtain optimal vehicle routes for the solid waste collection in the city of Campo Mourão, Paraná, Brazil. With the proposed methodology, authors were able to minimize the traveled distances and maintenance costs, as well as reducing environmental impacts.

VRPs are also considered to be NP-Hard problems and several methods can be used to solve them, including heuristic techniques. Regarding heuristics, specific strategies found in the literature can be divided into three types: (1) constructive heuristics, which seek the gradual construction of a viable solution with the lowest cost; (2) two-level heuristics, in which clients are first grouped into viable routes and then the actual routes are constructed; and (3) improvement methods which can act on a single route or on multiple routes [13]. The present work made use of a constructive heuristic, more specifically the Clarke & Wright savings (CW) algorithm, to solve a real-world problem faced by a waste collection company located in Portugal. In the next section, a detailed description of CW savings heuristic is presented.

A. *Clarke and Wright savings algorithm*

The CW algorithm is one of the most known heuristics for solving VRPs. This method aims to minimize the total distance traveled, which indirectly reduce the number of vehicles needed to meet all the points [19]. It was proposed by G. Clarke and J. Wright in 1964 [23] and introduced the savings concept which is based on the computation of savings by combining two customers into the same route. The general algorithmic approach is given below and consists of combining routes repeatedly by using one vehicle instead of two for the same set of customers while satisfying a given constraint. In other words, the basic idea is to use the savings that can be obtained, either in terms of distance traveled or in the time when joining two existing routes or points, to decrease collection or delivery costs [24]. First, the Euclidean distance matrix ($d_{i,j}$) is calculated with the following equation (Equation 1) [19]:

$$d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \qquad (1)$$

where x_i, y_i and x_j, y_j are the geographical locations of customer i and j. Second, the savings are obtained when the connection between customer i and the depot as well as the connection between the same depot and customer j are broken, creating a new connection between i and j (see Fig. 1) [18]. The savings value for each pair of customers between customer i and j can then be calculated as follows (Equation 2) [24]:

$$s_{i,j} = d_{1,i} + d_{j,1} - d_{i,j} \qquad (2)$$

where $d_{1,i}$ is the traveling distance between depot and customer i , $d_{j,1}$ is the traveling distance between depot and customer j, and $d_{i,j}$ is the traveling distance between customer i and j.

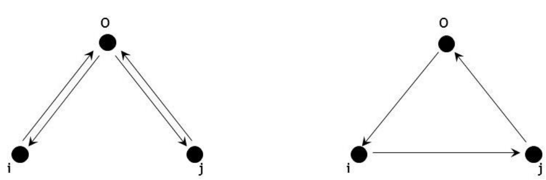

Fig. 1: Route merging procedure [24]

The values in the savings list are sorted in decreasing order and the route merging procedure starts from the top of the savings list (the largest $s_{i,j}$). Both customers i and j will be combined into the same route if the total demand does not exceed vehicle capacity and no route constraints exist. The route merging procedure is repeated until no feasible merging in the savings list is possible. Furthermore, in case of non-routed customers, each one is assigned by a route that starts at the depot, visits the unassigned customer, and returns to the depot [19].

Several applications of CW have appeared in the literature [13], [19], [25]. For example, the main aim of the research accomplished by [26], was to implement a model which would be able to find shortest and fastest routes, schedule the office bus, and also allocate bus stops for picking up and dropping employees at their residence. After applying the method, the transportation service was able to minimize traveled distances, time, number of stops and buses. In another work [13], authors solved a VRP of a food distributor. For that, an adaptation of the CW algorithm was used in order to incorporate the reality of deliveries in an urban environment, which occurs in a network with oriented pathways. The adopted heuristics showed that there was scope for reducing costs within the company since the number of vehicles in the proposed scenario was lower than the initial one [13].

III. MATERIAL AND METHODS

A. *Problem Statement*

The CW algorithm used in the present study aimed to solve the problem of vehicle routing of a Portuguese waste management company in order to find opportunities for cost reduction by identifying the optimal routes for sludge collection. This company performs various environmental services, including the management of sludge generated in several municipalities in Portugal. The collection of sludge occurs in four regions, namely Lisboa, Santarém, Azambuja, and Alenquer, with several points (customers) requiring a visit. There is a fleet consisting of 4 vacuum vehicles with different capacities which attends all these regions according to their demands (Table I). Currently, the company does not use any route optimization system, i.e., the vehicle leaves the starting point and attends each customer individually, returning to the origin to deposit the sludge in a drying bed after each point being visited. In a typical week, a specific vehicle goes to only one point per day, collects the sludge, and then returns to the origin.

The company operates in the region of Lisboa and Santarém with fixed points (WWTP) while in the regions of Azambuja and Alenquer the points are mostly random. Virtually, every vehicle may be used to meet the demands of each region. In this context, we decided to optimize and create routes for the fixed points (Case Study A) and then analyze a hypothetical case including several points in other two regions to which the company may extend its activities (Case Study B).

TABLE I. VEHICLES THAT MEET THE DEMANDS IN EACH REGION

Vehicle	Capacity (m^3)	Regions
A	6	Alenquer
B	9	Azambuja
B and C	9 and 12	Santarém
D	8	Lisboa

B. *Solution method overview*

The methodology adopted focused on the comparison of the present scenario used within the company with the solution generated by the algorithm using the vehicles already operating. The main goal was to reduce the traveled distance and costs by aggregating the demand of more than one point on the same route. The capacity of each vehicle was therefore defined as a constraint to find the optimal routes. The model was implemented in R [27] using a package (HeuristicsVRP [28]) containing functions relevant to route optimization. Specifically, the package was used to execute CW algorithm in parallel through the integration of the data presented in Table II. In general terms, the methodology was developed in six steps [29]:

Step 1. Location of points

Find the coordinates (longitude and latitude) of the points of the customers for the sludge collection.

Step 2. Distance between points

Calculate the Euclidean distances between all points, including the origin (drying bed).

Step 3. Savings computation

Compute the savings ($s_{i,j}$), for $i, j = 1,\ldots,n$ and $i \neq j$, and define the constraints (vehicle capacity).

Step 4. Savings List

Rank the savings ($s_{i,j}$) and list them in descending order. Process the savings list beginning with the topmost entry in the list (the largest ($s_{i,j}$)).

Step 5. Best feasible merge

Apply the algorithm by starting the analyses from the top of the savings list. For the savings under consideration, determine whether there exist two routes that can feasibility be merged: one starting with $(1, j)$, and one ending with $(i, 1)$. If no route constraints will be violated through the inclusion of (i, j), then combine these two routes by deleting $(1, j)$ and $(i, 1)$, and introducing (i, j).

Step 6. Route Extension

If the savings list has not been exhausted, return to Step 5, processing the next entry in the list; otherwise, stop.

An important percentage of the total collection cost is related to the transportation, so it was possible to calculate the cost spent on fuel based on the distances traveled in each route. For that, the fuel efficiency of the vehicle fleet was assumed to be 0.2 $km.L^{-1}$ (data provided by the company) and the diesel price 1.2 $€.L^{-1}$. Moreover, the GHG emission factor which allowed to estimate environmental impacts of vehicle operations was assumed to be 0.45 Kg CO2-eq.L^{-1} [9]. In the next section all the findings resulting from CW implementation are presented.

TABLE II. DATA REQUIREMENTS FOR ROUTE OPTIMIZATION BASED ON CW METHOD

Heuristic	Attributes
CW method	Depot and customers location
	Demand for each customer
	Vehicle capacity

IV. RESULTS AND DISCUSSION

A. *Analysis and comparison with company's practice: Case Study A*

In order to find a way to minimize the costs related to the distance traveled by vacuum vehicles while performing sludge hauling operations, the current collection system used by the company was analyzed by considering a typical week. The company visits twelve customers each week in the regions of Lisboa and Santarém, using three vehicles to meet the required demand. With this scenario, maximum vehicle capacity utilization only reaches 63% in Lisboa (Vehicle D) and 50% in some points in Santarém. Since the vehicles designated to perform sludge collection in the referred locations have higher capacities than the demands needed, it is clear that an opportunity to reduce costs is present.

CW algorithm was used to develop a novel weekly plan for the sludge collection system of the company (Table III). Numbers contained in the "Route" column refer to a specific collection point (customer), with number 1 being the starting point of the route. From the table, we verify that it is possible to merge two points (customers) on the same route if the vehicle with the maximum capacity is used. In order to better visualize the improvements obtained by applying this method, the savings on distance as well as the costs are plotted in Fig. 2. From the plot, we can compare both scenarios (the original weekly plan used by the company, and the novel weekly plan generated by CW algorithm). In general, it can be clearly seen that the total weekly savings achieve almost 40%, both for distance and cost. Specifically, with the adoption of the optimized plan, a single vehicle (Vehicle C) would be capable of performing sludge hauling operations in a given week for a fraction of the initial cost. Instead of three vehicles traveling 894 km every week, the company can meet customers' demand with only one vehicle traveling 548 km. In terms of average cost per unit of sludge collected and environmental impact in terms of pollutant emissions, these savings represent a decrease from 3.38 $€.m^{-3}$ to 2.06 $€.m^{-3}$, and 80 Kg $CO_{2\text{-eq}}$ to 49 Kg $CO_{2\text{-eq}}$, respectively. In other words, 1.32 $€.m^{-3}$ of sludge collected and 31 Kg $CO_{2\text{-eq}}$ could be saved every week.

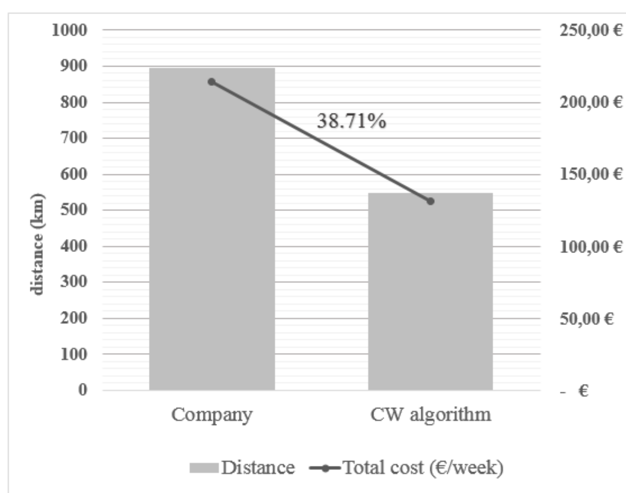

Fig. 2– Comparison between the original weekly plan (company's current situation) and application of CW algorithm

TABLE III. WEEKLY PLAN GENERATED BY CW METHOD FOR SLUDGE COLLECTION IN LISBOA AND SANTARÉM (CASE STUDY A)

Route	Vehicle capacity (m^3)	Total Demand (m^3)	Utilization	Distance traveled (km)	Variable vehicle cost (€)	GHG emissions (Kg CO_{2-eq})
[1 13 8 1]	12	12	1.00	147.99	35.52	13.32
[1 3 2 1]		10	0.83	87.67	21.04	7.89
[1 9 7 1]		10	0.83	92.71	22.25	8.34
[1 5 4 1]		10	0.83	65.83	15.80	5.92
[1 12 11 1]		12	1.00	89.25	21.42	8.03
[1 10 6 1]		9	0.75	64.55	15.49	5.81
			Total	547.99	131.52	49.32

From this analysis, we can also view taking out two vehicles from operating in the studied regions as another benefit, since the company would be able to expand its client portfolio because more vehicles and days would be available for performing other services in WWTPs. In this context, a new hypothetical scenario was studied based on the expansion of the company's activities to the nearby municipalities of Azambuja and Alequer. The findings resulting from the application of CW method to this new case study are presented in the next section.

B. *Expansion of company's activities: Case Study B*

For the expansion of company's activities to the municipalities of Azambuja and Alenquer, twelve WWTPs were selected as customers. From that, CW algorithm was applied to both regions combined and the available vehicles tested to simulate the sludge collection operations. The demands were estimated taking into account the real scenario (Case Study A) for the already existing clients and after some experimentation, Vehicle B was selected and its capacity (9 m^3) used as a constraint. The routes suggested by the application of the algorithm are shown in Table IV and a brief discussion follows.

From the table, it can be seen that the lowest vehicle capacity utilization refers the two routes that were not optimized (56%) since the capacity of the available vehicle (Vehicle B) was not enough to meet the demands on both points together (5 m^3 each). However, the other created routes presented a higher utilization rate for the vehicle, almost above 90%. Combining the scenario above with Case Study A, we found that the twelve new customers considered could be included in the collecting services while still reducing the initial cost faced by the company. In other words, for about 76% of the initial cost, the company would be capable of attending twice the number of customers. The total distance traveled for collecting sludge in the four regions would then be 683 km for a total vehicle cost of approximately 164 €/week. This approach clearly allows minimizing operating costs, both by reducing the number of vehicles of the company's fleet that have to be used, as well as total distance traveled.

C. *Sensitivity analysis*

A sensitivity analysis (SA) aims to check if a given model produces logical results when undergoing changes in the input parameters. With this approach, the stability of the solution provided by the model can be evaluated by allowing for a certain level of uncertainty. Usually, such analysis is performed in a condition where the effects of changing the value of a single parameter are considered while keeping the others constant [12]. In the present study, two parameters (vehicle capacity and fuel price) were used and their impact on model performance evaluated for the two scenarios already described (Case study A and B). Demand is also critical in route optimization, but their influence on the solution generated was not considered here given the features of sludge collection operations (for a given WWTP, the demand hardly changes week by week). For investigating the sensitivity to changes in vehicle capacity, CW method application was tested separately for both cases considered using the four vehicles owned by the company. As for fuel price, a 20% deviation was evaluated both above and below a baseline value (1.20 $€.L^{-1}$) while maintaining vehicle capacities constant (12 and 9 m^3, two vehicles - Vehicle C and Vehicle B). For each case examined, the percentage variation in terms of traveled distance (km) and savings variation in terms of real cost (€) were respectively calculated and analyzed. The results are presented in Table V and Table VI.

TABLE IV. WEEKLY HYPOTHETICAL PLAN GENERATED BY CW METHOD FOR SLUDGE COLLECTION IN AZAMBUJA AND ALENQUER (CASE STUDY B)

Route	Vehicle capacity (m^3)	Total Demand (m^3)	Utilization	Distance traveled (km)	Variable vehicle cost (€)	GHG emissions (Kg CO_{2-eq})
[1 4 2 1]	9	9	1.00	38.10	9.14	3.43
[1 6 5 1]		8	0.89	30.53	7.33	2.75
[1 7 3 1]		9	1.00	19.26	4.62	1.73
[1 10 9 1]		9	1.00	16.14	3.87	1.45
[1 12 11 1]		8	0.89	15.37	3.69	1.38
[1 8 1]		5	0.56	8.21	1.97	0.74
[1 13 1]		5	0.56	7.55	1.81	0.68
			Total	135.16	32.44	12.16

TABLE V. SA FOR BOTH SCENARIOS CONSIDERED SEPARATELY TAKING INTO ACCOUNT THE DIFFENT VEHICLES AVAILABLE (DIFFERENT CAPACITIES)

Vehicles	**Case study A (Lisboa and Santarém)**
A	Infeasible
B and D	Decrease of 3.48% in total traveled distance
C	Decrease of 38.71% in total traveled distance
Vehicles	**Case study B (Azambuja and Alenquer)**
A	Infeasible
B and C	Decrease of 33.90% in total traveled distance
D	Decrease of 16.82% in total traveled distance

TABLE VI. SA FOR BOTH SCENARIOS CONSIDERED SEPARATELY TAKING INTO ACCOUNT 20% DEVIATION FROM BASELINE FUEL PRICE (VEHICLE CAPACITY CONSTANT – VEHICLE C AND VEHICLE B)

Case study A (Lisboa and Santarém)	20% ↑	Savings of 57 € in total cost
	Baseline value	Savings of 83 € in total cost
	20% ↓	Savings of 109 € in total cost
Case study B (Azambuja and Alenquer)	20% ↑	Savings of 10 € in total cost
	Baseline value	Savings of 17 € in total cost
	20% ↓	Savings of 23 € in total cost

From these results, we verify that for Lisboa and Santarém the use of Vehicle A is infeasible due to insufficient capacity while Vehicles B and D do not present significant savings. However, by using Vehicle C it is possible to meet the demands required by the customers in both municipalities while achieving optimal savings of about 40% of the traveled distance. On the other hand, for Azambuja and Alenquer, either Vehicle B or C can perform sludge hauling operations while creating maximum savings (about 34%). In practice, Vehicle D may also be used, but traveled distance would decrease by only 17%. At this point, we should recall that in order to define a baseline for Azambuja and Alenquer a plan similar to the one currently used by the company for Lisboa and Santarém was considered, i.e., the vehicle which performs the work would visit only one customer in each route and return to the depot. Moreover, it is important to note that traveling time (including loading and unloading) was not taken into consideration in the analysis. As such, we cannot state if the vehicle with the higher capacity (Vehicle C – 12 m^3) would be available to collect sludge beyond the regions considered in the first case study. For simplicity, we consider that Vehicle C would attend the municipalities of Lisboa and Santarém, and Vehicle B would service the municipalities of Azambuja and Alenquer.

Regarding the variation in fuel prices, first it should be noted that any change in the fuel price will have no effect on the optimal routes generated by CW method since route selection depends only on the distance, demand and vehicle capacity. With this in mind, we opted to evaluate how different fuel prices would influence the variable vehicle cost (€) calculated for each route in the optimized scenario. From this, it is evident that the lower the fuel price considered the higher the saving generated by the adoption of the novel weekly plan in terms of variable vehicle cost. In particular, we verify that a drop of 20% from the baseline value would increase the savings generated by the aggregated routes from 83 to 109 €/week and 17 to 23 €/week in both case studies, respectively (Table VI). On the other hand, with a 20% increase in fuel prices, the savings would be less significant and fall to about 57 €/week and 10 €/week when compared with the baseline value (Table VI). In summary, it can be said that both vehicle capacity and fuel price are two important factors that may affect the viability of the proposed solution.

V. CONCLUSION

This study intended to apply the CW algorithm to the sludge collection system of a Portuguese company in order to optimize its routes. Two scenarios were analyzed. Results indicate that it is possible to maximize vehicle capacity utilization and minimize the number of vehicles needed for sludge collection in the regions under study. Specifically, with the application of CW algorithm in Case Study A, there is a weekly decrease in traveled distance and cost of 346 km and 83 €. These savings are mainly achieved by the optimization of the distance traveled to visit all customers, as well as a better utilization of the vehicles available. In addition, the optimized routes would allow a reduction in carbon dioxide emissions to the atmosphere of approximately 37 Kg $CO_{2\text{-eq}}$/week. We also found that the advantages of the use of CW algorithm go beyond route optimization since the new strategy allows the company to accept more customers without increasing costs. As such, in Case Study B, we conclude that it would be possible to attend 12 more customers in the municipalities of Azambuja and Alenquer while still reducing the initial cost from 215 € to 164 € for a reduction of 76%. Finally, based on sensitivity analysis, we found that vehicle capacity and fuel price are two important factors in route optimization with the savings generated greatly affected by the values considered in the two parameters. In particular, we conclude that the higher the capacity of the vehicle available, the higher the savings generated since more customers can be serviced in a single route. Also, as regards to the fuel price, it is evident that the savings generated change in proportion to the value considered, i.e., with higher fuel prices the savings generated by the adoption of the optimized plan become less significant in absolute values (€). In conclusion, CW algorithm may be regarded as a valuable tool for route optimization in companies facing real-world problems such as the collection of sludge in WWTPs with an important impact in operating costs. Globally, the achieved results can also be highlighted within the framework of Europe's 2020 strategy by improving transport efficiency and logistics at a local level.

ACKNOWLEDGMENTS

Authors acknowledge the financial support received by the project POCI-01-0145-FEDER-024020 (RDFGAS – Energy recovery of refuse-derived fuel (RDF) and dehydrated sludge), co-financed by COMPETE 2020 - Programa Operacional Competitividade e Internacionalização, Portugal 2020 and União Europeia through FEDER.

REFERENCES

[1] A. Raheem et al., “Opportunities and challenges in sustainable treatment and resource reuse of sewage sludge: A review,” Chem. Eng. J., vol. 337, no. December 2017, pp. 616–641, 2018.

[2] S. M. A. V. Carrilho and E. H. Carvalho, “Avaliação da disposição de lodos de fossa e tanque sépticos em lagoas de estabilização que tratam lixiviados de aterro sanitário,” Eng. Sanit. e Ambient., vol. 21, no. 1, pp. 183–196, 2016.

[3] B. M. Cieślik, J. Namieśnik, and P. Konieczka, “Review of sewage sludge management: Standards, regulations and analytical methods,” J. Clean. Prod., vol. 90, pp. 1–15, 2015.

[4] Q. Wang et al., “Technologies for reducing sludge production in wastewater treatment plants: State of the art,” Sci. Total Environ., vol. 587–588, pp. 510–521, 2017.

[5] M. Kacprzak et al., “Sewage sludge disposal strategies for sustainable development,” Environ. Res., vol. 156, no. January, pp. 39–46, 2017.

[6] L. D. Hauser, “Evaluating the Air Emissions from Solid Waste Refuse Trucks,” p. 280, 2015.

[7] European Federation for Transport and Environment, “Too big to ignore – truck CO 2 emissions in 2030,” no. September, pp. 2–4, 2015.

[8] E. Friedrich and C. Trois, “GHG emission factors developed for the collection, transport and landfilling of municipal waste in South African municipalities,” Waste Manag., vol. 33, no. 4, pp. 1013–1026, 2013.

[9] T. Fruergaard, T. Astrup, and T. Ekvall, “Energy use and recovery in waste management and implications for accounting of greenhouse gases and global warming contributions,” Waste Manag. Res., vol. 27, no. 8, pp. 724–737, 2009.

[10] M. K. Ghose, a K. Dikshit, and S. K. Sharma, “A GIS based transportation model for solid waste disposal--a case study on Asansol municipality.,” Waste Manag., vol. 26, no. 11, pp. 1287–1293, 2006.

[11] F. Li, B. Golden, and E. Wasil, “The open vehicle routing problem: Algorithms, large-scale test problems, and computational results,” Comput. Oper. Res., vol. 34, no. 10, pp. 2918–2930, 2007.

[12] T. P. B. Vecchi et al., “A sequential approach for the optimization of truck routes for solid waste collection,” Process Saf. Environ. Prot., vol. 102, pp. 238–250, 2016.

[13] L. H. Bremenkamp et al., “Aplicação Da Heurística De Clarke & Wright Para Um Distribuidora,” 2016.

[14] S. Raff, “Routing and scheduling of vehicles and crews. The state of the art,” Comput. Oper. Res., vol. 10, no. 2, 1983.

[15] A. Maryam and M. Yousefikhoshbakht, “A Combination of Meta-heuristic and Heuristic Algorithms for the VRP, OVRP and VRP with Simultaneous Pickup and Delivery,” BRAIN Broad Res. Artif. Intell. Neurosci., vol. 8, no. 2, pp. 81–95, 2017.

[16] C. D. Tarantilis and C. T. Kiranoudis, “Distribution of fresh meat,” J. Food Eng., vol. 51, no. 1, pp. 85–91, 2002.

[17] Z. Shen and F. Ord, “The Stochastic Vehicle Routing Problem for Large-scale Emergencies,” Work. Pap., pp. 1–33, 2007.

[18] S. R. de S. N. Cardoso, “Optimização de Rotas e da Frota Associada,” p. 103, 2009.

[19] T. Pichpibul and R. Kawtummachai, “A heuristic approach based on Clarke-Wright algorithm for open vehicle routing problem,” Sci. World J., vol. 2013, 2013.

[20] S. Das and B. K. Bhattacharyya, “Optimization of municipal solid waste collection and transportation routes,” Waste Manag., vol. 43, pp. 9–18, 2015.

[21] X. Bing, J. M. Bloemhof, T. R. P. Ramos, A. P. Barbosa-Povoa, C. Y. Wong, and J. G. A. J. van der Vorst, “Research challenges in municipal solid waste logistics management,” Waste Manag., vol. 48, pp. 584–592, 2016.

[22] A. Subramanian, E. Uchoa, and L. S. Ochi, “A hybrid algorithm for a class of vehicle routing problems,” Comput. Oper. Res., vol. 40, no. 10, pp. 2519–2531, 2013.

[23] G. Clarke and J. W. Wright, “Scheduling of Vehicles from a Central Depot to a Number of Delivery Points,” Oper. Res., vol. 12, no. 4, pp. 568–581, 1964.

[24] J. M. Crespo Carvalho, Logística, 3a Edição. Lisboa: Edições Sílabo, Lda., 2004.

[25] M. Alameen, R. Aljamal, and S. Damrah, “A Clarke and Wright Improved Algorithm to Solve the Vehicle Routing and Traveling Salesman Problem,” Glob. J. Enterp. Inf. Syst., vol. 8, no. 1, p. 35, 2016.

[26] E. K. Hashi, M. R. Hasan, and M. S. U. Zaman, “A heuristic solution of the Vehicle Routing Problem to optimize the office bus routing and scheduling using Clarke & Wright’s savings algorithm,” 1st Int. Conf. Comput. Inf. Eng. ICCIE 2015, pp. 13–16, 2016.

[27] R. R Development Core Team, R: A Language and Environment for Statistical Computing, vol. 1, no. 2.11.1. 2011.

[28] N. Kaveti, “HeuristicsVRP: Implementation of heuristic algorithms for finding greedy routes.” 2017.

[29] L. Caccetta, M. Alameen, and M. Abdul-Niby, “An Improved Clarke and Wright Algorithm to Solve the Capacitated Vehicle Routing Problem,” Technol. Appl. Sci. Res., vol. 3, no. 2, pp. 413–415, 2013.